Tailings surface cover development through integration of reactive phosphate and organic matter

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Abstract
In 1993, two 0.5 ha experimental plots were set up on inactive uranium tailings in Elliot Lake and on fresh pyrrhotite tailings at Copper Cliff, Ontario. Phosphate rock and horse manure were mixed into the tailings surfaces by a roto-tiller. Field plots were investigated using electromagnetic resistivity measurements 39 months (Copper Cliff) and 45 months (Elliot Lake) after set up. Resistivity measurements on the pyrrhotite tailings when modeled showed distinct differences between treatment plots, with phosphate treatments having the highest resistivity. At the same time, treatment plots were sampled both within and below the amended tailings surface stratum. The samples were stored for 5.5 years (Copper Cliff) and 6.5 years (Elliot Lake), respectively, at room temperature in the dark. Slurries (1:5 w:v) to assess the chemistry, simulating pore water in the tailings layer were made. The supernatant was monitored for 22 months by periodically measuring pH, redox potential, electrical conductivity, and acidity. At the end of the monitoring period, the elemental composition of the supernatant was determined by ICP. Principal component analyses (PCA) were applied to parameters that were measured in the simulated pore water. With the PCA performed on the water quality data, differences in treatment conditions were determined within the uranium tailings and the base metal tailings plots. It was possible to discriminate between treatment conditions in terms of pore water characteristics in the uranium and the base metal pore water. The PCA indicated that the pyrrhotite tailings treatment with high horse manure and high phosphate generated distinct water quality conditions, but only in the amended surface layer at a depth of 7.5 cm. High horse manure and high phosphate improved the pore water quality in both tailings types.

Introduction:

Acid generation originates at the surface of pyritic material through oxidation processes. This chemical weathering, together with microbial activity, lead to the formation of secondary precipitates and generation of hydrogen ions, enhancing leaching (Nordstrom, 1982). Preventative measures for acid generation would have to consist of limiting the oxidation potential at the surface of the sulphide mineral. Instead, the conventional approach is to treat the metal-laden acid effluent through adding acid-neutralizing material, generating secondary wastes as sludges which are disposed mostly back into the tailings pond (Gurung et al., 2000). Microbial growth-inhibiting agents have been tested, but they are difficult to apply to the mineral surface and they have a finite effectiveness (Meek, 1991; Nyavor et al., 2002). Spotts and Dolhopf (1992) added phosphate mine products to coarse coal wastes and achieved essentially the inhibition of acid generation from the piles. They mixed the coal wastes with 1 to 5 % phosphate rock. These high mixing ratios are impractical in mining waste management. Recently, several workers have addressed the role of phosphate on pyrite oxidation with various results (Fuller et al., 1997; Georgopoulou et al., 1996; Chen et al., 1997b; Nyavor and Egiebor, 1995). The generally promising results on the inhibition of acid generation lead us to the formulation of cover approach PHITO (Phosphate-Heterotroph Inhibition of Tailings Oxidation). Phosphate wastes from the Texasgulf Aurora phosphate mine in N.C are used in PHITO to assist hardpan formation when applied on the surface of the tailings together with rich organic matter. Conceptually, seasonally upward-rising metal-laden pore water would encounter phosphate-rich pore water, leading to secondary mineral precipitation in the tailings pore spaces. The organic matter supports oxygen-consuming heterotrophic bacteria, which initially assist reducing oxidation. A hardpan would thus slowly form resulting in reduced infiltration of oxygen-rich atmospheric precipitation. Although this concept sounds reasonable, proof that PHITO may be a viable concept for tailings

management has to be obtained through evidence from field tests on actual tailings sites. Laboratory studies and geochemical/microbial considerations provide theoretical validity of the approach. However, the complexity of the AMD problem dictates that the translation of scientifically-reasonable concepts to practical solutions is difficult and often fails.

We therefore selected extremely adverse conditions to test the PHITO concept. The PHITO concept was applied to test plots established in fresh pyrrhotite tailings which are exposed on the tailings pond beaches (Inco, Copper Cliff, Ontario) and on old uranium tailings (Denison, Elliot Lake, Ontario) which are stripped of any neutralizing minerals due to the sulphuric acid leach to extract uranium. In addition to these very adverse conditions, time is required as the weathering reactions are slow. The observations reported in this paper cover a span of 8 years. The plots were set up in l993 and the final assessment was completed in 2001 when laboratory measurements of simulated pore water ended.

Experimental Methods

INCO, Copper Cliff: The INCO tailings at Copper Cliff, Ontario represent one of the world largest Cu /Ni tailings areas. As part of the tailings management practice, pyrrhotite tailings form a separate waste stream, being deposited in isolated areas from the main tailings. Approximately 3000 m^3 or 4000 t of fresh pyrrhotite was trucked to a section of the tailings pond where observations could be made over a longer period, as this area was no longer active and had developed a relatively stable surface. The material was spread to a nominal thickness of 0.5 m over about 0.5 ha. The experimental area sloped gently (1-2 % grade) from north to south towards a pond, where water was collected for treatment in the liming plant. A set of test plots was created consisting of 45 m x 51 m subsections. The fresh pyrrhotite tailings, although very reactive, exhibited a high initial pH (4 to 7).

Denison, Stanrock Tailings: The Stanrock tailings originated from uranium mining between 1958 and 1964. Surface stabilisation was marginal by l993 and, due to the sulphuric acid leach used to extract uranium, the tailings had a low pH ranging from 1.9 to 2.5. The marginal indigenous vegetation (2 small trees and sparse grass) was removed from the surface to set up the 1,300 m^2 experimental area.

Natural Phosphate Rock (NPR) and manure:
As many studies addressed phosphate and metal interactions using either synthetic phosphate minerals or processed phosphate products from the Aurora phosphate deposit in North Carolina, mined by Texasgulf we selected mining wastes from this operation. One hundred t of mining waste product from this phosphate deposit were shipped by rail. The mining wastes referred to as Natural Phosphate Rock (NPR) contained 7.1 % P as calcium phosphate, compared to fertilizer products sold by the mine which contain 13 % or more total P. The other main constituent of the waste is Ca (31 %), mostly in the form $CaCO_3$. The horse manure was aged for at least 2 years and was obtained for both sites from local stables.

Experimental Setup*:* Twenty seven treatment plots were created, arranged in 3 m x 9 m subplots on the Inco tailings and 4 m x 11 m on the Stanrock tailings, for a total area of 0.07 ha and 0.12 ha, respectively**.** Phosphate rock (NPR) and horse manure (HM) were spread using a PTO-driven fertilizer spreader pulled by a tractor. Plots were seeded with oats by a seed drill. Using a hydro-seeder truck, water was sprayed over the entire plot as a dust control measure. On the Stanrock tailings, the plots were set up using a garden roto-tiller since the surface was not stable for access by heavy machinery. All 27 plots were tilled to a depth of about 10 cm. The Stanrock plots were seeded by hand.

In Table 1 the application rates and the plot numbers are given. Even if the cover development with this approach were to show promising results, its application would not progress if it were not economical. Hence the low application rate of NPR was dictated by the cost of replacing lime, regularly used to stabilize tailings surfaces, with NPR. The high NPR

application rate was determined based on laboratory assessments.

Table 1: Test Conditions at Copper Cliff and Stanrock.

Condition	Plot #s
No NPR, No HM	1,6,7
No NPR, Low HM , (1.6 L m^{-2})	2,5,8
No NPR (10 L m^{-2}), High HM (10 L m^{-2})	3,4,9
Low NPR (3 kg m^{-2}), No HM	10,15,16
Low NPR (3 kg m^{-2}), Low HM (1.6 L m^{-2})	11,14,17
Low NPR (3 kg m^{-2}), High HM (10 L m^{-2})	12,13,18
High NPR (30 kg m^{-2}), No HM	19,24,25
High NPR (30 kg m^{-2}), Low HM (1.6 L m^{-2})	20, 23,26
High NPR 30 kg m^{-2}), High HM (10 L m^{-2})	21,22,27

In situ leachate generation: Eighteen 1 m deep holes were excavated for the placement of Leachate Collection Devices (LCD). They consisted of a funnel placed on a 1 L cylinder. The funnel was filled with glass wool and covered with fiberglass window screening. The LCDs are connected to the surface with two PVC tubes to retrieve water samples. The holes were carefully backfilled by hand in order to ensure that the tailings were well compacted around the devices.

EM – Conductivity: Geomar Geophysics Ltd.(Toronto, Ontario) employed electro-magnetic conductivity meters (Geonics EM31 and EM38) to map the subsurface conductivity within the study area.
Using the grid for control, EM31 (Vertical and Horizontal dipole mode) and EM38 survey lines were laid out in a N-S direction at a 2.5 m spacing over the entire site**.** The EM38 in vertical mode has an exploration depth of 1.5 m.

The electromagnetic data were collected in continuous mode with a time interval of 0.5 seconds, which corresponds to approximately 0.5 meter between readings. A fiducial marker was used every 15 m (matching the survey grid) along the survey lines. The EM31, employed in the vertical dipole mode, has an exploration depth of 6 m and is relatively insensitive to surface interference. Soil conductivity measured in this mode ranges from 60 to 120 $mS.m^{-1}$, which corresponds to borehole resistivity data greater than 1 m for this area (King, 1994).

Resistivity: The relationship between hydraulic conductivity and electrical conductivity (or resistivity) is well known. Since a hardpan under the tailings would decrease permeability (or hydraulic conductivity), the electrical conductivity will differ from the surrounding medium. The presence and extent of a hardpan layer beneath the surface might be investigated non-intrusively by measuring the tailings' resistivity over and around the test plots. Resistivity surveys were also conducted by Geomar Geophysics Ltd. The electrodes were uniformly spaced in a line. One or two measurements were made in each of the 27 subplots. Two stations in the tailings, 15 m and 30 m west of the experimental plots, were measured in order to compare results of soundings at locations unaffected by the NPR.
An ABEM Terrameter SAS 300 instrument was used to measure resistivity. Four readings were taken for each probe spacing and the average value was used for analysis. Since the high conductivity of the tailings limited the maximum probe spacing, the number of probe spacings was increased in order to obtain high quality sounding curves for the upper layers of the soil.

Tailings Sampling Methods: Tailings samples were obtained with a shovel from different depths in May 1997, 4 years after the set-up of the 27 subplots at both sites. Samples were collected at 3 depths, 0-15 cm (the original actively-tilled layer), 16-30 cm, and, at INCO, a sample below 30 cm. The samples were bagged (sterile Whirlpac®), placed in coolers and stored at room temperature to facilitate microbial activity that would generate acid.

In January 2000, six years after set up, forty (40) grams of sample were weighed and combined with 200 mL of distilled water to make a slurry (1:5 w:v). The slurry was stirred for one minute and then allowed to settle for 1 hour. Twelve mL of supernatant were centrifuged at 2000 rpm to remove suspended particles. The temperature, pH, Eh (in mV), electrical conductivity ($\mu S.cm^{-1}$), and acidity

were measured for each supernatant sample. The slurries were stored at room temperature covered with parafilm to prevent evaporation. Periodic re-measurements of the same parameters were made to arrive at a definite the endpoint of acid generation reactions. These slurries were simulating tailings pore water chemistry.
At the end of the experiment, the supernatant was filtered through a 0.45 μm filter paper, acidified to a pH of less than 1 with nitric acid and analysed by a certified, analytical laboratory with Inductively Coupled Argon Plasma Spectroscopy, determining elemental concentrations in $mg.L^{-1}$.

Statistical Methods: The analytical approach considered the impact of treatment using principal component analysis (PCA) on the standardized elemental supernatant concentrations derived at the endpoint of the experiment and on the set of measurements of the physical/chemical water quality data, respectively. All respective measurement values were uniformly scaled to a mean of zero and a standard deviation of one and processed by principal component analysis, for both sites and all layers.
Laboratory aggregate measurements of water quality, including hydrogen ion concentration (pH), conductivity ($\mu S.cm^{-1}$), acidity ($mg\text{-}CaCO_3.L^{-1}$) and oxidation-reduction potential (E_h in mV) were considered juxtaposed to the results of the elemental analysis of the supernatant. The ICP elements included: Al, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Si, Sr, Ti, V, Zn, and Zr. Phosphorus (P) concentrations were not included in the multivariate analysis as P was the key aspect of treatment and the objective was to investigate the impact of treatment itself. The samples of the treatments were grouped by soil depth as follows: level 1 (0-15 cm), level 2 (15-30 cm), and level 3 (>30 cm).

The first principal component from the PCA on the physical/chemical measurements could be interpreted as an Acid Mine Drainage Index (AMDI). A low AMDI value suggests a potentially beneficial condition, while a high AMDI value represents more adverse chemistry associated with untreated tailings.

The first principal component of the PCA on the elemental chemistry was interpreted as the Tailings Pore Water Index (TPWI). The indices were highly correlated to each other as would be expected (Figure 1). The high correlation substantiates the use of the physical/chemical parameters for their ability to adequately reflect the pore water elemental chemistry, which were only measured once, at the end of the experiment.

Results

Leachate water was retrieved from the LCDs in September l993 from the Stanrock tailings three months after set up. The acidities in all plots ranged from 7,569 to 28,073 $mg\text{-}CaCO_3 .L^{-1}$. These values were considered background pore water quality in the field plots. After 6 months (May 1994), the acidities were lower, ranging from 1,467 to 18,657 $mg\text{-}CaCO_3 .L^{-1}$, with the lowest values collected from the high phosphate-high manure plot. For both these initial sampling dates, the LCDs in the Inco tailings were dry. While these results were encouraging, the possibility existed that the spring melt contributed to the lower values. In May l997, 3.5 years after set up, the LCDs were re-sampled. The acidities were generally higher than three years before, ranging from 546 to 22,236 $mg\text{-}CaCO_3 .L^{-1}$, again with the lowest values in the high NPR treatment, with a reduction from 13,272 to 546 $mg\text{-}CaCO_3.L^{-1}$. At that time the Inco LCDs contained sufficient pore water for collection. The acidity values were highly variable, ranging from 47 to 7,777 $mg\text{-}CaCO_3.L^{-1}$. These values could not be related to the treatment plots. It should be noted that the LCD's funnel area, 0.018 m^2 , is three to four orders of magnitude less than the combined surface area of the three replicates for each treatment, i.e., only small spots were assessed.

As the Stanrock LCD's were quite promising, an EM survey of selected plots in the experimental area was conducted with two electromagnetic conductivity meters (EM31 and EM38) in l996 in both test plots. These surveys revealed relatively poor correlation between plots with NPR and HM and changes in conductivity. Electromagnetic conductivity meters are tools

that are very sensitive to small changes in electrical cconductivity of the subsurface, however, at the same time, they are very good detectors of conductive material. The pyrrhotite has a very high electrical conductivity that masks the small effects of a subsurface resistive hardpan created by the NPR. Resistivity measurements might better reflect changes due to the treatment. However the resistivity results obtained on the Inco plot suggested no hardpan but a higher resistivity in the 15 –26 cm layer, with readings ranging from 72.1 to 147.6 Ω.m and from 9.0 to 12.0 Ω.m for the layer between 40–70 cm. The readings were consistently lower over the entire plot of 0.12 ha. The resistivity is not related to the treatment plots, but surface resistivity is higher than at depth, suggesting mainly surface reactions in the tailings and supporting in principal the concept of PHITO addressing the shallow layer of the tailings.

From the stored samples collected in and below the treatment layers on both sites, slurries were made to monitor pore-water chemistry changes in the lab with time. For the Inco tailings, the control plot pore-water slurries ranged from a low of 66 to a high of 5,715 mg-$CaCO_3$ $.L^{-1}$ (n=5), which is a range similar to plots with the low application rate of NPR. Lower acidities of 106 to 321 mg-$CaCO_3$ $.L^{-1}$ (n= 5) were associated with the high treatments. In the lower layers, a large variability of acidities of the pore-water was observed, ranging from 59 to 4,032 mg-$CaCO_3$ $.L^{-1}$ (n=30). No pattern with respect to treatment could be discerned.

While the pore water acidities were variable in samples collected from the Stanrock plots, some trends can be seen. The surface layer of tailings (0-15 cm) had lower acidities than the lower layers (15-30 cm); the acidities of surface samples from the control plots ranged from 378 to 713 mg-$CaCO_3$ $.L^{-1}$ (n=7), while the acidity of samples at depth ranged from 2,070 to 8,604 mg-$CaCO_3$ $.L^{-1}$. The acidities of samples from plots with High NPR application rates ranged from 10 to 40 mg-$CaCO_3$ $.L^{-1}$ (n=14). In the second layer, the variability with treatment was high; for instance in the treatment "No NPR/ High HM", acidities ranged from 89 to 465 mg-$CaCO_3$ $.L^{-1}$ (N=7).

Table 2: Elemental concentrations mg.L^{-1} and acidity in mg-$CaCO_3$ $.L^{-1}$.

TREATMENT	pH	Acidity	Al	Cu	Fe	P	Zn
INCO (0-15 cm)							
No NPR, No HM	3.06	6715	870	0.68	43	0.22	9.3
No NPR, High HM	3.14	5639	730	1	23	0.2	13
Low NPR, No HM	3.24	3864	520	1.3	19	0.16	8.5
High NPR, No HM	3.84	1090	120	17	0.1	6.9	5.3
High NPR, High HM	7.19	10.7	-0.01	0.04	0.22	-0.01	0.01
INCO (15-30 cm)							
No NPR, No HM	3.08	3232	420	19	28	0.03	7
No NPR, High HM	3.16	3076	420	0.66	19	0.06	7.7
Low NPR, No HM	3.04	3429	460	33	20	0.02	6.4
Low NPR, High HM	3.15	2954	400	11	21	0.04	7.4
High NPR, No HM	3.09	4032	560	19	23	0.08	8.4
High NPR, High HM	3.11	3389	440	9.3	24	0.08	7.7
STANROCK (0-15 cm)							
No NPR, No HM	2.67	656	50	0.59	18	0.03	0.98
No NPR, High HM	2.68	558	34	0.42	12	0.02	0.29
Low NPR, No HM	2.77	491	18	0.59	56	0.62	0.45
Low NPR, High HM	4.52	38.7	2.8	0.01	0.26	2.5	0.08
High NPR, No HM	6.75	39	-0.01	0	0.01	0.05	-0.01
High NPR, High HM	7.37	9.7	-0.01	0.01	0.26	0.16	-0.01
STANROCK (15-30 cm)							
No NPR, No HM	1.86	8604	66	1.6	2910	2	1.6
No NPR, High HM	3.37	88.5	3.3	0.05	0.23	-0.01	0.04
Low NPR, No HM	1.82	8471	86	0.74	2690	15	1.3
Low NPR, High HM	4.45	43.2	2.4	0.02	0.01	2.6	0.17
High NPR, No HM	1.99	6066	51	0.97	2060	190	0.71
High NPR, High HM	1.83	4782	110	1.6	3410	64	2.2

The assumption was made that, in the slurry, only those elements which are mobile would be found in the tailings pore water and would ultimately be detected in seepage at the bottom of the tailings dam. As expected, the elements Al and Fe reflect the largest decreases in the treatment layer 0-15 cm as they represent a major component of the metal acidity used to monitor the slurries (Table 2). However, the elemental concentrations start to vary and increase in the deeper layers of 15 to 30 cm. For both Inco and Stanrock plots, the same trend is noted, namely, the release of metals from the treatment layer was lowest samples from the

High NPR/High HM plots. The simulated pore-water concentrations in the second layer are also presented to emphasize the large variability.

To determine a trend in a data set with such a large variability, statistical methods are needed to assess the significance of the differences between treatments and the layers. Using Principal Component Analysis, we formulated the AMDI and the TPWI which correlated the chemical and the physical measurement of the slurries well (Figure 1) and thus reflect the pore water characteristics. To assess the statistical differences between the treatments and layers, we have used the AMDI index, presented in summary in Figure 2. The AMDI expresses the correspondence between rising conductivity, acidity and E_h with a decreasing pH. The aggregate AMDI is an effective pore water descriptor, and it accounts for 76 and 86 percent of the variability expressed in the water quality data for the Inco and Stanrock samples, respectively.

Since all the NPR and HM were tilled into the first 10-15 cm of the tailings, one would expect that this layer would be the most affected by any treatment. The second layer, between 15 and 30 cm, would be below the "hardpan" and might have received some dissolved phosphate. However, the horizons below 30 cm were probably unaffected by the surface PHITO. These results do suggest the potential for a systematic relationship to all treatments in the surface layer. For the second layer (15-30 cm) the High NPR, but no HM produced values similar to the control; thus, at depths below treatment, the effect of the treatment is not expressed.

The acid generation in the tailings pore water could be quite intense, as can be noted from the acidity values obtained from the LCD samplers one meter below the treatment plots. These values were generally higher than the acidity values in the simulated pore water made from the tailings samples. The key question is, has the treatment arrested or reduced the acid generation rate? This topic might be addressed through standardizing the acidity values obtained by the successive measurements. An acid generation rate can be obtained by subtracting the acidity value of the initial slurry. This acidity represents the result of that acid generated in the field treatment plot for three years, as well as that generated during storage in moist conditions at room temperature for 3 more years. Storage may have provided suitable conditions to obscure variation between samples due to treatments imposed in the field.

This initial acidity at the start of the measurement period was subtracted from the acidity at end of the period and divided by the number of days to obtain an acidity generation rate ($CaCO_3$ equivalent) in units of $ml.L^{-1}.day^{-1}$. If the value is zero or close to zero, no acid was generated (Figure 3).

The pH of the Inco tailings slurry with no NPR overall declined from pH 3.5 to 3.0 during the 630 day period. The acidity generation rate was 17 to 28 $mg.L^{-1}.d^{-1}$ during the three periods over the first seven days, diminishing to less than 9 $mg.L^{-1}.d^{-1}$ for the 4-175 day and 175-525 day periods. Acidity generation rate increased over the final period (525-630 days) to 28 $mg.L^{-1}.d^{-1}$.

The pH of the Inco tailings slurry treatment with low NPR also declined over the experimental period, from an initial pH of 3.9, down to3.2 by 630 days. The acidity generation rate was very low at the outset (2 $mg.L^{-1}.d^{-1}$), but increased over the first seven days to 38 $mg.L^{-1}.d^{-1}$. The acidity generation rate diminished thereafter to 4 to 9 $mg.L^{-1}.d^{-1}$.

In contrast, the pH of the Inco high NPR treatment gradually increased over the 630 day period from pH 3.4 to 3.8. After an initially high acidity generation rate (31 $mg.L^{-1}.d^{-1}$) during the 3-7 day period, the rate declined to 2.5 $mg.L^{-1}.d^{-1}$ or less from the remainder of the period.

The long term trends in pH and acidity generation rates for Stanrock tailings slurries are relatively straight forward. The pH of the control (no NPR) and low NPR treated tailings gradually declined from pH 2.9 to 2.7 over the 630 day period. The pH of tailings slurries treated with high NPR treatment increased from

pH 6.1 to 6.8. Acidity generation rates for the control and both NPR treatments diminished to near zero over the first seven days and remained very low for the remainder of the experimental period. In the low NPR treatment, some of the initial acidity was removed in the first period, while most acidity was removed by the high NPR treatment.

The results of this long-term lab experiment indicate that the high NPR treatment can greatly reduce the acidity generation rate in Inco tailings. Meanwhile, Stanrock tailings did not generate acidity over the 630-day period in the given conditions, and high NPR appears to have only neutralized acidity already existing in the samples prior to set-up.

Conclusions

The objective of the work was to prove the concept of the PHITO cover under adverse field conditions. We have used three methods to evaluate the use of phosphate rock and heterotrophic microbial systems to reduce acid generation. The pore water collected in the field indicated improvement with the high treatment of NPR and HM. Although we did not find indication of hard pan formation, we determined uniform resistivity at the surface and at depth in the highly reactive pyrrhotite tailings at Inco. The third method, evaluation of acidity generation rates in slurries over the 6 years since set up, showed reduced acid generation rates in Inco pyrrhotite tailings and cessation of acid generation in Stanrock tailings, by then 36 years old. By choosing the old Stanrock tailings for comparison to Inco's reactive pyrrhotite tailings, the inhibitory effects of PHITO on the actively acid-generating Inco tailings could be more clearly demonstrated.

From the large variability of the tailings pore water characteristics within treatments, it is evident that proving inhibitory activity on acid generation is a complex task. The PHITO treatment has neutralizing capacity as demonstrated by the Stanrock results, but its lasting effect under the adverse conditions tested in the pyrrhotite tailings is the more encouraging result. Lime neutralizes through consuming hydrogen ions, which leads to the precipitation of metal hydroxides, which can be expected to deteriorate in these conditions. NPR, on the other hand, releases calcium carbonate and phosphoric acid which, in turn, bind with metals. Given the acid generation rates noted and the length of time the samples were exposed, the cumulative acidity generated is likely to exceed the neutralisation capacity of this one-time application of the NPR.

Compositional analysis of water quality data obtained during the monitoring of NPR and HM amendments at the Inco and Stanrock tailings sites indicates that the treatment had a greater impact on water quality at the Stanrock test site but, in general, the high application rates exhibited the greatest impact on the pore water quality with respect to control plots over the monitoring period.

In conclusion, the data suggest that the application of PHITO could reduce acid generation. Recent results of field applications on Zn/Cu tailings in Buchans, Newfoundland are providing additional support of the PHITO concept (in preparation).

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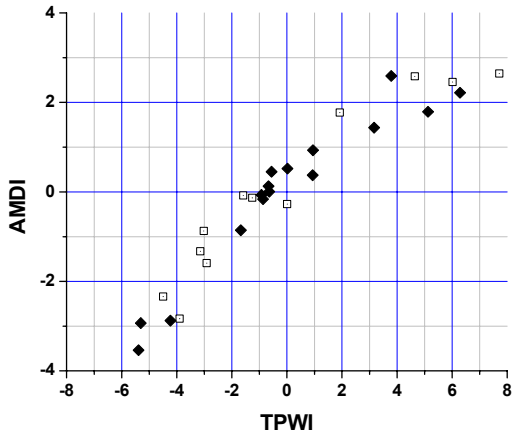


Figure 1: Correlations between the tailings pore water index (TPWI) and the acid mine drainage index (AMDI), for the INCO (♦) and Stanrock (□) tailings pore water. The AMDI is the first principal component from PCA on the scaled aggregate water quality parameters and the TPWI is the first principal component from PCA on the scaled elemental chemistry.

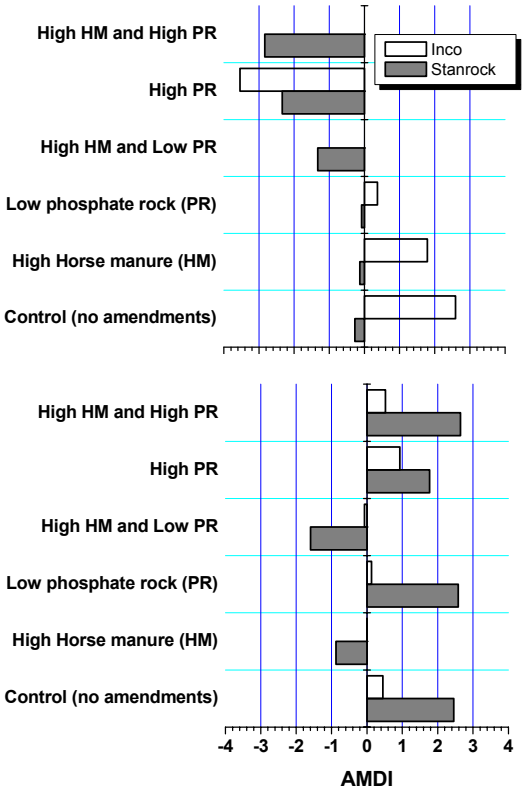
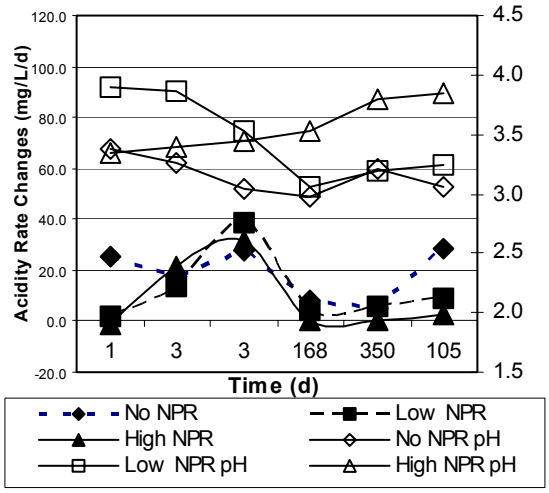


Figure 2: The Inco and Stanrock AMDI for the surface (top) and underlying (bottom) layers. The surface layer represents a depth range from 0-15 cm. The underlying layer is from 15-30 cm. High NPR and HM appear to promote lower AMDIs. Note that no bar indicates missing data.



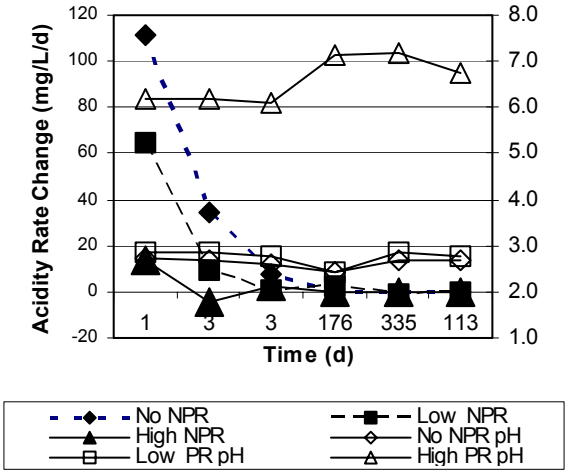


Figure 3: Acidity rate changes and pH values for Inco (top) and Denison (bottom) in simulated pore water slurries. The rate of change was calculated by subtracting the acidity at t_0 from t_1 and dividing by the elapsed time in days.